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Eye Movement Correlates of Younger and Older Adults' Strategies for Complex
Addition

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Abstract

This study examined performance measures and eye movements associated with complex arithmetic strategies in young and older adults. Participants added pairs of 3-digit numbers using two different strategies, under choice and no-choice conditions. Older adults made more errors but were not significantly slower than young adults, and response times and errors showed no interaction between age and the number of carries. Older adults chose strategies less adaptively than young adults. Eye movements were consistent with use of required strategies on no-choice trials and reported strategies on choice trials. Eye movement data also suggested that young adults more successfully distinguished between strategies. Implications of these findings for understanding aging effects in complex arithmetic are discussed.

Eye Movement Correlates of Younger and Older Adults' Strategies for Complex Addition

The fundamental goal of research in arithmetic is to understand how people accomplish arithmetic problem solving tasks. Examining determiners of participants' performance has helped to build models of arithmetic processing (see Campbell, 2005; Dehaene, 1997; Geary, 1994, for overviews). Previous research has shown that arithmetic performance is influenced by a variety of factors such as participants' characteristics (e.g., age, Lemaire, Arnaud, & Lecacheur, 2004), situational constraints (e.g., solving problems while providing verbal protocols or not, Kirk & Ashcraft, 2001), cognitive strategies (e.g., retrieving the solution directly from long-term memory or calculating, Torbeyns, Verschaffel, & Ghesquiere, 2002), and problem features (e.g., problem size, Zbrodoff, 2005). The present study aimed at further understanding the role of participants' age in three-digit addition problems and the role of one seldom-investigated problem feature (i.e., carry, when the sum of digits in a position is greater than or equal to 10). More specifically, we wanted to understand how people process carries in addition tasks and age-related differences in this processing. The second goal of this study was to determine the usefulness of eye-movement data to study strategies in arithmetic processing in particular and in cognitive aging in general. Before presenting the logic of the present experiment, we review previous findings first on arithmetic problem solving and second on strategy and eye movements.

Arithmetic and Aging

Previous research has shown that when solving arithmetic problems, participants use different strategies, and their performance is affected by problem features. A strategy can be defined as "a procedure or a set of procedures for achieving a higher level goal or task" (Lemaire & Reder, 1999, p. 365). Different aspects of strategies include strategy repertoire (which strategies people use), strategy distribution (the

relative frequency of each strategy), strategy selection (how strategies are chosen), and strategy execution (relative speed and accuracy of strategies; Lemaire & Siegler, 1995). A useful method for studying strategies is the choice-no choice method (Siegler & Lemaire, 1997) which requires participants to complete a task using a mandated strategy (no-choice condition), and using a free choice of strategies (choice condition). No choice trials allow a measure of strategy execution independent of strategy selection, whereas choice trials allow investigation of strategy repertoire, distribution, and selection.

Age-related differences in strategies for solving simple problems have been extensively studied (see Duverne & Lemaire, 2005, for a review). For example, Geary and his collaborators analyzed verbal reports of young and older adults in a simple addition production task. They observed differences in young and older adults' strategy repertoire (see also Allen et al., 2005; Lemaire & Lecacheur, 2001). Both age groups reported using retrieval (i.e., solving 9-4 by directly retrieving 5 from memory) and decomposition strategy (i.e., solving 7-4 by doing 7-2-2). Young adults used a decomposition strategy on easier problems (7%) more often than older adults (2%) and retrieval less often than older adults (88% vs. 98%; see also Geary & Lin, 1998, for similar findings in subtraction problems; Geary, Frensch, & Wiley, 1993).

Strategies have been much less investigated for complex than simple arithmetic problems. Studies have focused on children, with a number of studies from mathematics education demonstrating use of different strategies by children in solving complex addition and subtraction problems (e.g., see Beishuizen, 1993; Fuson et al., 1997). We do not know much about adults' age-related differences in complex arithmetic and in strategies used to solve complex problems. The present study was a first step in this direction.

The second important set of robust findings from previous research on arithmetic concerns effects of problem features on participants' performance. One of the best documented problem features is problem size. Participants have better performance on smaller problems such as 3×4 ; $12 + 23$ than on larger problems such as 6×7 ; $38 + 43$ (see Zbrodoff & Logan, 2005, for a review). One much less investigated problem feature, which is studied here, is carry.

Reaction time and factor analytic methods have shown that execution of carries is an elementary process involved in arithmetic (along with processes such as encoding, calculating, retrieving arithmetic facts, and responding). First, participants are slower with carry problems (i.e., such as $18 + 27$) than with no-carry problems such as $21 + 24$ (Geary & Widaman, 1987; Widaman, Geary, Cormier, & Little, 1989). Second, Frensch and Geary (1993) found that, in complex addition verification by university undergraduates, carries became reliably faster with practice whereas time to encode a single digit or to retrieve addition facts did not change with the amount of practice. The authors' follow-up experiments suggested that this result was more likely to be due to representing sequences of carry task components in memory (termed composition) than solely to strengthening by repetition (Frensch & Geary, 1993). Third, dual-task studies with mental arithmetic have shown an important role of executive processes in carrying (Fürst & Hitch, 2000; Kondo & Osaka, 2004; Seitz & Schumann-Hengsteler, 2002).

Comparisons of young and older adults have shown mixed results. Two studies reported that older adults have less difficulty in managing carries (Geary et al., 1993; Geary & Lin, 1998) whereas another one reported that they have more difficulty (Salthouse & Coon, 1994). In both Geary et al.'s and Salthouse and Coon's studies, young and older adults solved subtraction problems with (e.g., $87 - 9$) or without borrow (e.g., $86 - 4$). Older adults were faster than young adults at executing the borrow procedure in Geary et al.'s studies but slower in Salthouse and Coon's study. Accuracy

was similar between the younger and older groups within each study. As discussed by Salthouse and Coon, one possible explanation for the discrepancy is that Geary et al.'s older adults were more educated than Salthouse and Coon's participants. Given that no definite conclusions can be reached regarding age-related differences in managing carries, we decided to test them further in a different arithmetic operation, namely addition, where they have never been tested before.

Strategy and Eye Movements

One important issue when investigating cognitive performance from a strategy perspective is the way strategies are measured. Verbal reports have generally been found useful and valid measures of strategies (Robinson, 2001; Smith-Chant & LeFevre, 2003). Reports of strategies for arithmetic can sometimes be validated by observation, especially in children (Siegler, 1987). Analysis of performance measures such as response times or accuracy also helps to validate strategy self-reports in arithmetic tasks (Geary et al., 1993; Penner-Wilger, Leth-Steensen, & LeFevre, 2002; Smith-Chant & LeFevre, 2003). Nevertheless, some limitations with verbal reports have been identified, including problems of reactivity and veridicality (Robinson, 2001). Also, different instructions have been found to bias participants' reports of strategy in simple arithmetic (Kirk & Ashcraft, 2001), particularly for participants with lower arithmetic skills (Smith-Chant & LeFevre, 2003). Other concerns include the potential that participants may have insufficient explicit knowledge to be able to accurately report strategies.

An additional, non-invasive method that can provide insight into strategy use is recording eye movements. Point of regard identified from eye movement data is assumed to correspond to the mental operation currently being performed (Grant & Spivey, 2003; Just & Carpenter, 1987; Suppes, 1990). Eye movements have been a valuable tool for investigating a number of cognitive domains, including reading

(Meseguer, Carreiras, & Clifton, 2002), evaluating art (Zangemeister, Sherman, & Stark, 1995), visual search (Ho, Scialfa, Caird, & Graw, 2001), driving simulations (Mapstone, Roesler, Hays, Gitelman, & Weintraub, 2001), chess (Charness, Reingold, Pomplun, & Stampe, 2001), and visually guided motor responses (Ko, 2001; Land & McLeod, 2000). There has been limited application of eye movement techniques in investigating cognitive processes associated with arithmetic, although the method seems well suited to this domain.

While a number of studies have used eye movements to investigate arithmetic word problems (e.g., De Corte, Verschaffel, & Pauwels, 1990; Hegarty, Mayer, & Monk, 1995; Lieven Verschaffel, de Corte, & Pauwels, 1992), only a few published studies have reported eye movements during arithmetic with Arabic numeral stimuli. Suppes and colleagues recorded eye movements of two adults and three children while participants completed arithmetic tasks of addition and subtraction (Suppes, 1990; Suppes, Cohen, Laddaga, Anliker, & Floyd, 1983). Problems were presented in column format and participants were instructed to use the standard processes taught in schools for problems presented in this manner. Fixation durations were reported to correspond well with the required strategy. A significant proportion of variance in fixation durations was associated with structural features such as the number of columns and the presence or absence of carry or borrow requirements.

Verschaffel and colleagues used eye movements to assess 8 and 9 year-old children's strategies for adding three numbers together (Verschaffel, De Corte, Gielen, & Struyf, 1994). Single-digit addends were presented in a horizontal line and the sequence of fixations at least 100 ms in duration was identified. The final gaze that lasted at least 180 ms was assumed to be the number that participants added to the other two operands. In 62% of cases the strategy inferred from eye movements concurred with the participants' trial-by-trial verbal reports of strategy. Children made extensive

use of rearrangement strategies: In 71% of cases when a rearrangement was possible they rearranged so as to first add either two complementary numbers that summed to 10 or two identical numbers.

Eye movement data have also been reported for “matchstick” arithmetic, in which participants had to determine how to rearrange matchsticks arranged as Roman numerals so that incorrect equations became correct equations (Knoblich, Ohlsson, & Raney, 2001). Eye movement data, like in other studies of insight problem solving (e.g., Grant & Spivey, 2003), showed that successful problem solvers spent more time fixating on features relevant to the solution than did unsuccessful problem solvers. In sum, previous studies have indicated that eye movements show correspondence with arithmetic strategies, can be sensitive to problem features, and are likely to be a useful method for further investigation.

Overview of Study

The aims of this study were to (a) further our understanding of how people solve complex arithmetic problems in general and process carries in particular, using a strategy perspective, (b) investigate age-related differences in processing carries, and (c) investigate the usefulness of eye-movement data to examine strategies in arithmetic and age-related differences in these strategies. Participants’ task was to add two 3-digit numbers using mental arithmetic and verbally report the result. A pilot study in young adults identified use of different strategies, with two main strategies. These were starting by adding the unit digits, then the decades, then the hundreds (named “unit strategy” for this study). The other was adding hundreds, then decades, then units (“hundred strategy”). Older and younger participants were instructed about these two strategies and completed the task under both choice and no-choice conditions (Siegler & Lemaire, 1997) while their eye movements were recorded.

We hypothesized that (a) older adults' performance would be slower than young adults', especially with more carries, (b) young and older adults would differ in strategy adaptiveness (as seen in cumulative duration longer for hundred digits at the beginning of the trial while using hundred strategy and for unit digits while using the unit strategy), and (c) different strategies would be associated with different patterns of eye movements.

Method

Participants

Participants were 24 university students aged 20-25 and 24 community-dwelling older adults aged 60-83 years ($M = 68.0$, $SD = 6.1$ years). Older adults came from a pool of volunteers who had attended public talks on cognitive aging given by the second author. Participants completed paper-and-pencil tests of Mini-Mental Status (Folstein, Folstein, & McHugh, 1975). For skill measures separate from the main experimental task, participants completed paper-and-pencil tests of arithmetic (addition and subtraction-multiplication subtests from the French kit; French, Ekstrom, & Price, 1963) and vocabulary (French version of the Mill-Hill Vocabulary Scale; Deltour, 1993; Raven, Court, & Raven, 1986). They also self-rated their health from 1-7, 7 being the highest. These results are reported in Table 1. Older participants performed significantly better than young adults on tests of arithmetic ($p < .001$) and vocabulary ($p < .05$) but performed significantly worse than young adults on a mini mental status examination ($p < .001$; see means in Table 1).

 Insert Table 1 about here

Stimuli

The stimuli were 72 addition problems presented in the form $\underline{a} + \underline{b}$, where \underline{a} and \underline{b} were three-digit numbers with a mean correct sum of 765 (range 320-980). Stimuli are listed in the Appendix. Problems were generated using random digits that were grouped into six consecutive digits (i.e., pairs of three-digit operands). Based on previous research (see Ashcraft, 1995; Campbell, 2005; Dehaene, 1997; Geary, 1996 for reviews), problems were excluded if (a) either operand had 0 in the hundred or unit position, (b) either operand had 5 in the unit position, (c) both operands had the same digit in the same position, (d) digits were repeated within an operand, or (e) a pair of operands previously used was repeated, in either the same or reverse order.

Problems that passed these criteria were selected consecutively until there were 24 trials in each of three conditions. The three conditions were matched for mean correct sum and were no carry (correct sum 373-977, $\underline{M} = 762$), one carry in either the unit or decade positions (320-980, $\underline{M} = 767$), and two carries (carry in both the unit and the decade position; 425-955, $\underline{M} = 765$). For one-carry trials, half had the carry in the unit position and half had the carry in the decade position. Problems were divided into three blocks of 24 trials which were matched for mean correct sum (766, 766, and 763 respectively). Within each condition and within each block, the largest unit and largest operand occurred equally often in left and right positions for half the problems.

Apparatus

Problems were presented in 56-point Arial black font on white background in the centre of a IBM-compatible computer monitor. Participants sat 70-100 cm from the screen, meaning that each digit occupied 0.95-1.35 degrees of visual angle. E-Prime software controlled the stimulus display and collected response times. Eye movements were recorded with an iView® X Remote Eyetracking Device (Senso-Motoric Instruments). A camera located next to the participant's visual display unit, on the participant's right, tracked the location of the right pupil. Simultaneous tracking of the

corneal reflex allowed the system to compensate for minor head movements. Participants were asked not to make too many head or body movements but no device restricted them from moving. Calibration was performed by requesting participants to view nine crosses on the screen. Recalibration was performed between each block if necessary. Eye position was sampled every 20 ms and analyzed offline using customized software.

Procedure

Participants were told that they would see problems on the screen in which they would add two numbers, with three digits in each number. They were told how many blocks, trials within each block, and practice trials they would complete. They were asked to say the answer aloud as quickly as possible, but only when they were sure of the answer.

Each trial began with a central fixation point (asterisk) followed after 750 ms by horizontal presentation of the problem. Timing of each trial began when the problem appeared and ended when the experimenter clicked a mouse button. The experimenter clicked as soon as possible after the participant finished speaking the response, and then recorded the participant's answer and strategy report. Pilot testing showed that if response time was taken from when the participant began the answer, they may then have further hesitations or stumbles. Previous trials in our laboratory have shown the alternative method of voice keys to be particularly problematic for older adults due to triggering of the key by processes such as coughing, the participants speaking to the experimenter, or participants beginning an incorrect response and then correcting themselves. Also, similar procedures have been reported previously for response time involving addition of three digit numbers (Fürst & Hitch, 2000). The response time measure used in the present study includes variance associated with the experimenter,

but this is in the order of tens of milliseconds whereas response times are in the order of seconds.

Participants were told that there were two main ways to complete the task and were instructed how to use the unit and hundred strategies. Three blocks were then presented, the order of blocks being determined by a Latin-square design. The first block was a “choice” block in which participants were permitted to use either strategy. After each trial, the participant reported which strategy they had used. Blocks 2 and 3 were “no-choice” blocks; consecutive participants alternated between using unit and hundred strategy on their first no-choice block. During no-choice blocks, participants were asked to tell the experimenter if they varied from the strategy type they were meant to use on that trial. The 24 trials within each block were randomized for each individual. Rests of 2-10 minutes between blocks were provided. Before the experimental trials, participants completed paper-and-pencil tasks and eight practice problems to familiarize themselves with the apparatus, procedure, and task.

Results

Performance

Due to positive skew in response time data, data trimming was applied such that trials longer than the participant’s mean plus two standard deviations were replaced with the participant’s mean response time for trials answered correctly. The proportion of trials trimmed in this way was 4.6% and 5.4% of trials for young and older adults respectively. For each participant, the percentage of errors within each condition was computed, along with mean response time for trials with correct responses. Two-way ANOVAs with age (between-participants: young, older) and carry (within-participants: 0, 1, 2 carries) were used to analyze mean response times and percent errors on choice trials. No-choice trials were analyzed with three-way ANOVAs with factors of age, carry, and strategy (within-participants: hundred, unit).

Means and standard deviations for response times, percent errors, and strategy use for each age group and carry number are shown in Table 2. On no-choice trials, older adults made significantly more errors ($\underline{M} = 18.4$, $\underline{SD} = 19.8\%$) than young adults ($\underline{M} = 13.0$, $\underline{SD} = 14.0\%$), $F(1, 46) = 4.58$, $p < .05$. The main effect of carry was also significant, $F(2, 92) = 29.21$, $p < .001$: Errors increased significantly with each additional carry. Choice trials showed the same pattern of errors, with main effects of age, $F(1, 46) = 6.42$, $p < .05$, and carry, $F(2, 92) = 20.74$, $p < .001$. There were no other significant main effects or interactions for percent errors.

Insert Table 2 about here

Response times for no-choice trials increased significantly with each added carry, leading to a main effect for carry, $F(2, 90) = 92.82$, $p < .001$. The same pattern was seen for response times on choice trials, $F(2, 92) = 101.28$, $p < .001$. On no-choice trials, carry also interacted with strategy, $F(2, 90) = 7.20$, $p < .01$. Participants were significantly faster on no-carry trials when required to start by adding the hundreds, $\underline{M} = 6.4$, $\underline{SD} = 2.4$ s, than when required to start by adding units, $\underline{M} = 7.3$, $\underline{SD} = 2.2$ s, $p < .001$. Conversely, there was a trend for participants to respond more slowly on trials with two carries when required to start with hundreds, $\underline{M} = 12.3$, $\underline{SD} = 5.5$ s, than with units, $\underline{M} = 11.8$, $\underline{SD} = 4.0$ s, $p = .057$. Response times were similar for one-carry trials whether required to start by adding hundreds, $\underline{M} = 9.7$, $\underline{SD} = 4.5$ s, or units, $\underline{M} = 9.9$, $\underline{SD} = 3.4$ s. There were no other significant main effects or interactions for response times.

Strategy Selection

In order to investigate strategy selection in choice trials, a two-way ANOVA was carried out with age (between-participants: young, older) and carry (within-participants: 0, 1, 2 carries) as independent variables and percent use of unit strategy as

the dependent variable. The number of carries had a significant main effect on mean percent use of the unit strategy, $F(2, 92) = 27.01, p < .001$. The greater the number of carries, the higher was the percentage of use of the unit strategy (see Table 2). Although there was no main effect of age on strategy use, there was an interaction of Age x Carry, $F(2, 92) = 4.73, p < .05$. As shown in Table 2, the increase in use of unit strategy with a higher number of carries was greater in young people, $F(2, 46) = 24.19, p < .001$, than in older people, $F(2, 46) = 5.24, p < .01$.

Next, for each age group, stepwise problem-based regressions were computed with percent use of unit strategy as the dependent variable and independent variables of correct sum, carry number, relative strategy speed in no-choice (response time with hundred strategy minus response time with unit strategy), and relative strategy accuracy in no-choice (percent errors with hundred strategy - percent errors with unit strategy).

The regression analyses, summarized in Table 3, showed that higher percent use of unit strategy was significantly associated with higher carry number in young and older adults (squared semipartial correlations, $\underline{sr}^2 = .60$ and $.16$ respectively). However, relative strategy speed was a significant predictor in older adults ($\underline{sr}^2 = .18$), but not in young adults. The direction of the correlation of relative strategy speed and percent use of unit strategy showed that with increased speed advantage of unit over hundred strategy, older participants were less likely to choose unit strategy, the opposite correlation to that which would be predicted.

Insert Table 3 about here

Eye Position at Beginning of Trial

Eye movements in correct trials were analyzed in terms of zones, similar to the methods reported by other researchers (Hodgson, Bajwa, Owen, & Kennard, 2000;

Verschaffel et al., 1994). Zones of regard were identified around each of the six digits (excluding the far left, right, top and bottom of the screen and the zone around the plus sign). The zone for each digit was 41 pixels (1.64 cm) wide and 400 pixels (16 cm) high. When at least three consecutive data points occurred within the same zone (representing a minimum of 60 ms), the duration was added to the cumulative total for that zone. Zones were summed across operands for the hundred, decade, and unit digits. To examine the extent to which participants conformed with the required strategies, cumulative durations during the first second of each no choice trial were analyzed as Age (2) x Strategy (2) x Digit (3) x Carry (3). The number of fixations was analyzed in the same way, with fixation onset determined by the occurrence of at least three consecutive data points within close proximity in the same zone and fixation offset defined as outlying data points from the fixation cluster.

Because participants could choose their own strategy on choice trials and did so according to level of carry, a minority of participants had eye movement data available for choice trials in all six combinations of carry and strategy. Thus, to retain maximum participant numbers for eye movement analyses of choice trials, cumulative durations and fixations were averaged over levels of carry and analyzed as Age (2) x Strategy (2) x Digit (3). Results of the ANOVAs for eye movements in the first second of choice and no choice trials are shown in Table 4. Due to increased likelihood of Type I errors with multiple analyses, discussion of results in the text focuses on effects with a probability level of .01 or smaller.

Insert Table 4 about here

No Choice Trials

For cumulative durations, main effects were found for strategy and digit. The strategy effect occurred because cumulative duration was significantly longer when participants were required to use the hundred strategy, $\underline{M} = 0.22$, $\underline{SD} = 0.13$ s, than when they were required to use the unit strategy, $\underline{M} = 0.20$, $\underline{SD} = 0.14$ s. The digit effect showed that cumulative duration was longest for decades ($\underline{M} = 0.25$, $\underline{SD} = 0.11$ s), followed by units ($\underline{M} = 0.22$, $\underline{SD} = 0.14$ s), then hundreds ($\underline{M} = 0.15$, $\underline{SD} = 0.13$ s).

There was a significant interaction of Strategy x Digit which was modified by a three-way interaction of Age x Strategy x Digit. The two-way interaction was consistent with participants applying the strategies they were required to use (see Figure 1). Participants looked at the hundred digits significantly longer when asked to use hundred than unit strategy, and looked significantly longer at unit digits when asked to use unit than hundred strategy. Cumulative duration for the decade position did not differ significantly between the two strategies. The interaction with age showed that differentiation between strategies was greater in young than in older adults (see Figure 1). The number of fixations showed similar results to cumulative durations, in terms of both size and direction of effects.

Insert Figure 1 about here

Choice Trials

The same digit effect was found as for no choice trials (see Table 4), with cumulative duration and number of fixations greatest for decades, then units, then hundreds. There was no main effect of strategy. A Strategy x Digit interaction for cumulative durations paralleled the pattern for no choice trials (compare Figures 1 and 2) but was not as pronounced as for no choice trials and did not reach significance for

the number of fixations. A trend towards an Age x Strategy x Digit interaction was present in choice trials for both cumulative duration, $p = .053$ and fixations, $p = .021$. In contrast to no-choice trials, young adults showed a trend towards a Strategy x Digit interaction within the first second but older adults did not (see Figure 2).

Insert Figure 2 about here

Eye Position Across the Trial

To investigate the spatio-temporal distribution of attention during each trial, eye movements were analyzed during each quarter of the total trial length. These analyses used cumulative durations and number of fixations as for the first second of the trial, and involved factors of Age (2) x Strategy (2) x Time (4) x Digit (3) x Carry (3) for no choice trials. Choice trials were averaged over levels of carry and analyzed as Age (2) x Strategy (2) x Time (4) x Digit (3). Results of the ANOVAs for eye movements in the choice and no choice trials are shown in Table 5.

Insert Table 5 about here

No Choice Trials

Main effects on cumulative duration were found for time, digit, and carry. Although there was an equal amount of time in the four quarters, time spent fixated on digit positions was greater in the second ($\underline{M} = 0.58$, $\underline{SD} = 0.54$ s) and third ($\underline{M} = 0.57$, $\underline{SD} = 0.50$ s) quarters than in the first ($\underline{M} = 0.54$, $\underline{SD} = 0.52$ s) and fourth ($\underline{M} = 0.55$, $\underline{SD} = 0.48$ s) quarters. Similar to the first second, cumulative duration was greatest on decades ($\underline{M} = 0.75$, $\underline{SD} = 0.59$ s), followed by units ($\underline{M} = 0.55$, $\underline{SD} = 0.46$ s) then hundreds ($\underline{M} = 0.36$, $\underline{SD} = 0.38$ s). Consistent with response time increases, cumulative

duration increased with the number of carries. The number of fixations showed the same digit and carry effects but no main effect of time, suggesting that cumulative duration increased in some quarters due to longer fixations rather than an increased number of fixations.

There were also a number of two-, three- and four-way interactions, described below. For cumulative durations, significant two-way interactions were found for Time x Strategy, Time x Digit, Time x Carry, and Digit x Carry. The Time x Strategy interaction revealed that, in the first quarter, cumulative duration was significantly longer for the hundred ($\underline{M} = 0.56$, $\underline{SD} = 0.57$ s) than unit ($\underline{M} = 0.51$, $\underline{SD} = 0.46$ s) strategy, $p < .001$, but in other quarters there was no significant difference between strategies ($\underline{M} = 0.54$ - 0.58 s for hundred strategy and $\underline{M} = 0.55$ - 0.58 s for unit strategy). The Time x Digit interaction showed that cumulative durations peaked for decades in the second quarter, hundreds in the third quarter, and units in the fourth quarter. An interaction of Time x Carry showed that the time effect, with a peak cumulative duration in the second quarter, was more pronounced the higher the number of carries. The Digit x Carry interaction occurred because the digit effect was more pronounced the more carries there were.

Significant three-way interactions of Age x Time x Digit and Time x Strategy x Digit were further modified by a significant four way interaction of Age x Time x Strategy x Digit (see Figure 3). The interactions were consistent with both young and older adults applying the strategies required: Time spent gazing at hundreds was greater earlier in the trial when the hundred strategy was required but greater later in the trial when the unit strategy was required; the reverse was seen for units. However, young adults showed greater differentiation between strategies than older adults (see Figure 3).

Insert Figure 3 about here

Interactions of Time x Strategy x Carry and Time x Digit x Carry were modified by a significant interaction of Time x Strategy x Digit x Carry. These interactions showed that cumulative duration on different digits over the four quarters was consistent with the required strategies being applied. The effect of increased carries was most prominent when the strategy required processing of that digit. For example, with a hundred strategy, the carry effect on cumulative duration for the hundreds was significant in the first but not the last quarter, but, with a unit strategy, the carry effect for hundreds was significant in the last but not the first quarter. There was no five-way interaction.

Choice Trials

Choice trials showed the same pattern of the time main effect for cumulative duration as for no-choice trials, with longer durations in the second and third quarters than the first and final quarters. Like no-choice trials, there was no main effect of time for fixations. The digit effect was the same as for choice trials. Time x Digit and Age x Time x Digit interactions seen in no-choice trials were weaker or did not reach significance on choice trials. However, the key Time x Strategy x Digit interaction was present on choice trials and had the same pattern as no-choice trials, demonstrating that eye movements were consistent with the trial-by-trial strategies reported by participants. There was a trend towards an Age x Time x Strategy x Digit interaction for choice trials with the same pattern as that seen in no-choice trials (Figure 3). That is, there was a trend for younger participants to show more strongly differentiated eye movements corresponding to different strategies. An additional interaction was present in choice but not no-choice trials: this Age x Digit interaction occurred because both groups fixated longest on decade positions (\underline{M} = 0.69 and 0.93 for younger and older respectively), but young people fixated longer on units (\underline{M} = 0.63) than hundreds (\underline{M} =

0.29) whereas the reverse was seen for older participants ($\underline{M} = 0.45$ and 0.71 for units and hundreds respectively).

Discussion

When participants completed a complex addition task under choice and no-choice conditions, we found that specific strategies were suited to specific problem types, and young participants chose strategies more adaptively than older participants. Eye movements validated participants' use of the required (no choice) or reported (choice) strategies and showed that older participants' strategies were less clearly differentiated than those of young participants. These findings have implications for further understanding of aging and complex arithmetic and for using eye movements in studying strategies in arithmetic processing in particular and in cognitive aging in general.

Implications for Further Understanding Complex Arithmetic and Aging

The present findings document strategies in complex arithmetic and carrying; they also document age-related differences in complex arithmetic. Both young and older adults used the unit and hundred strategies for three-digit addition problems. These strategies were associated with different patterns of eye-movements, solution latencies, percent errors, and percent use, and these measures varied with age and problem types. Use of the unit strategy increased with a higher number of carries. Moreover, the hundred strategy was found to be faster than the unit strategy when no carries were required, comparable to the unit strategy with one-carry problems, and showed a trend towards being slower when two carries were required. Finally, during the first second of trials, participants spent more time looking at units when using the unit strategy and more time fixating hundreds when using the hundred strategy.

The second set of interesting findings in this experiment concerns how participants process carries. The present results confirm that participants have better

performance on no-carry problems than on carry problems; they also show that performance declines with more carries. These carry effects are consistent with previously reported similar effects (Geary & Widaman, 1987; Widaman et al., 1989). As suggested by previous studies on the role of executive processes in carrying (Fürst & Hitch, 2000; Kondo & Osaka, 2004; Seitz & Schumann-Hengsteler, 2002), such carry effects are easy to understand if we consider the extra steps required to process carry. When participants solve carry problems, they have to encode digits, to find single-digit sums in long-term memory (or count), to temporarily hold partial sums and to add triplets of digits. Temporarily holding partial sums and adding triplets place extra working-memory demands that are not required while solving no-carry problems. The present findings suggest that carry effects may also be the result of participants using different sets of strategies, as problems with more carries were accompanied by increased use of the unit strategy. Recall that the unit strategy yielded slower latencies on problems with more carries. Thus, increased use of the slowest strategy combined with extra processing demands led participants to have poorer performance with carry problems than with no-carry problems. Observing a contribution of strategies to carry effects is interesting as such a strategy contribution has also been observed in other problem feature effects in arithmetic. Indeed, LeFevre and her colleagues (LeFevre, Bisanz, Daley, Buffone, & Sadesky, 1996; LeFevre, Sadesky, & Bisanz, 1996) have observed that small-operand problems tend to be solved more frequently with easier strategies. Combined with correct solutions to smaller problems being more easily retrieved from memory (or better execution of retrieval strategy), this greater use of an easier strategy on small problems led participants to have better performance on small problems. More generally, these data suggest that effects of problem features in arithmetic stem from both use of different strategies and different levels of strategy execution.

Another set of interesting findings here concerns aging effects in complex arithmetic. Older adults were not significantly slower than young adults, although there was a clear trend in this direction, and they made more errors than young adults. Response time included time used for speaking the answer. As noted earlier, Fürst and Hitch (2000) also measured latency from stimulus onset to response completion, considering this sufficient accuracy for response times in multiple seconds. Their typed response was in the specified order of unit, then decade, then hundred. Inclusion of the spoken response in the response time measure would not account for the lack of a significant response time difference with aging, as response execution is one of the aspects frequently found to be affected by aging (Allen et al., 1992; Allen et al., 1997; Duverne & Lemaire, 2004, 2005; Geary & Lin, 1998).

Most surprisingly, there was no Age x Carry interaction for response times or errors. A number of arithmetic studies have found increased age effects with increased complexity (Campbell & Charness, 1990; Myerson & Hale, 1993; Salthouse, 1992; Salthouse & Coon, 1994; Verhaeghen, Kliegl, & Mayr, 1997), but their absence or even inverse favoring older adults (Geary et al., 1993; Geary & Lin, 1998) has also occurred previously. As mentioned by several authors, arithmetic may be a special cognitive domain where aging effects are not always as robust as in other domains (e.g., Geary et al., 1993). For example, the Age x Problem Size effect (i.e., increased young-old difference with increasingly difficult problems) is often not found (e.g., Allen et al., 1992; Allen et al., 2005; Allen et al., 1997; Duverne & Lemaire, 2004; El Yagoubi, Lemaire, & Besson, 2003, 2005; Geary & Lin, 1998).

As mentioned by Salthouse and Coon (1994), it is possible that cohort or skill effects may be at stake in arithmetic, with young participants being less mathematically skilled than older adults. Such cohort effects would also explain the fact that young adults were more influenced by the number of carries in their strategy use: Older adults

increased their use of the unit strategy as a function of the number of carries less than young adults. Note though that cohort effects may not be responsible for the lack of Age x Carry interaction here. First, although our older adults tended to have higher scores in the pencil-and-paper arithmetic fluency test, they obtained poorer accuracy scores in our three-digit addition problem solving tasks. Second, cohort effects predict that older participants would use the unit strategy much more often than they did in this experiment. This would happen because older adults would use the unit strategy most of the time if not on all problems. This clearly did not happen here as older adults' strategy use was influenced by the number of carries and as young adults used the unit strategy more often than older adults on problems with more carries. The difference between no-carry and carry problems in mean percent use of the unit strategy was larger in young adults (36.9%) than in older adults (14.9%). This is consistent with the hypothesis that older adults may be less flexible in their strategy use (see Duverne & Lemaire, 2004; Lemaire et al., 2004 for similar conclusions in other arithmetic tasks).

Using Eye-Movement to Study Arithmetic and Aging

An original feature of this study was the collection of eye-movements. They proved useful in looking at arithmetic strategies and aging and also provided insight regarding temporal and spatial distributions of attention during problem encoding and solving.

Eye-movement data provided converging evidence for carry effects and strategy use. Consistent with performance data, cumulative eye fixation durations were longer on carry than on no-carry problems, suggesting that while they fixated participants not only encoded pairs of digits but also added them. This replicates effects of problem features on eye-movement data reported by several authors (Suppes, 1990; Suppes et al., 1983; Verschaffel et al., 1994). Moreover, cumulative durations during the first second of the trial were consistent with participants' using the required unit and hundred

strategies: Cumulative durations were longer on unit digits than on hundred digits while using the unit strategy and the reverse while using the hundred strategy. These cumulative duration differences were larger in young adults than in older adults. Analysis of the full length of trials showed a similar pattern of results: Participants had cumulative durations consistent with required strategies but the pattern in young adults differentiated between strategies more strongly than the pattern in older adults.

Importantly, choice trials showed that eye movements validated participants' reported trial by trial strategies. The difference in eye movements between the two strategies was attenuated in the first second for both younger and older adults for choice compared with no choice trials (compare Figures 1 and 2), which is likely to reflect additional time needed for encoding and strategy selection on choice but not no choice trials. For older adults, the Strategy x Digit interaction in the first second of choice trials did not reach significance, suggesting that older adults took longer for encoding and strategy selection than younger adults. Processes such as encoding and response selection in arithmetic have been shown to be more slowed by aging than processes such as arithmetic fact retrieval (Geary & Lin, 1998). Eye movements in both age groups were consistent with reported strategies in choice trials over the full length of the trial.

In both the first second and over total trial length, decades were looked at longer than units which were looked at longer than hundreds. This is consistent with the "optimal viewing position effect" found in reading, such that fixations tend to be close to the word's centre (Radach, Krummenacher, Heller, & Hofmeister, 1995). It is possible that people may look at groups of digits together. These fixations would, on average, be most likely to be counted as "decade" fixations. The lack of carries on hundreds may have also resulted in decreased time spent looking at hundreds.

Nevertheless, it would be of interest to see whether this pattern of cumulative duration on different digits would be replicated.

A main effect was also found for time, operationalized as the four quarters of the trial: Cumulative durations in digit zones were greatest during the second and third quarters of the trial. Increased carries were associated with quantitative but not qualitative changes in other effects: Effects such as the digit and time effects were more pronounced the higher the number of carries. This has some similarity with eye movements on a Tower of London task, in which more complex problems were associated with increased fixations on central positions (Hodgson et al., 2000). Similarly, the effect of increased carries was most prominent when the strategy required processing of that digit, such as the finding that with a hundred strategy, the carry effect on cumulative duration for the hundreds was significant in the first but not the last quarter.

Results for the number of fixations were similar to results for cumulative durations, except for the absence of a time main effect. This provides converging evidence for the eye movement results. The different results for time suggest that increased cumulative durations during the second and third quarters were due to longer lasting fixations rather than an increased number of fixations.

Limitations of This Study

Although solution times, accuracy, and eye-movement data provide support for distinguishing among strategies, it is necessary to acknowledge that strategies here were simplistically divided into two (unit vs. hundred) strategies. Future studies would help us better understand the details of how people solve multi-digit arithmetic problems by running more fine-grained analyses than here. This could be done both in terms of encoding strategies and calculating strategies. The use of the unit and hundred strategies in this experiment suggests that more encoding strategies may be distinguished. For

example, further variations within the hundred strategy have been noted in the mathematics education literature (Beishuizen, 1993; Fuson et al., 1997). This includes the “split” and “jump” strategies. In “split” strategy, the hundreds, decades, and units are each added in pairs and the subtotals are then added together (e.g. $153 + 219 = 100 + 200 = 300$, $50 + 10 = 60$, $3 + 9 = 12$; $300 + 60 + 12 = 372$). In “jump” strategy, the second addend is decomposed into hundreds, decades and units and these are sequentially added to the first addend (e.g. $153 + 219 = 153 + 200 + 10 + 9 = 372$). Similarly, participants could be probed on how they compute (encoding and adding one pair of digits at a time vs. encoding several pairs of digits followed by calculating). More detailed, trial-by-trial verbal protocols may help in refining descriptions of the complete strategy repertoire that participants use to solve complex arithmetic problems.

Although the present findings show that eye movement data are a valuable tool to assess arithmetic strategies and age-related differences in arithmetic processing, future studies should consider one aspect in the present data. Eye movement data presented here do not account for the entire trial length. For example, in the first second of the trial, the mean durations fixated on the three digit positions sum to the equivalent of 0.66 s in young and 0.60 s in older adults. This age difference was significant, although there was no main effect of age over the total trial length. The “other” time is accounted for by fixations outside the designated zones: the plus sign and the far left, right, top, and bottom of the screen, as well as movements or fixations of less than 60 ms duration. Older adults may have had more difficulty in allocating attention initially; they are however equally able as young adults to allocate attention during the problem solving process. Another unexpected finding in the first second was that there was greater cumulative duration in digit zones for hundred than unit strategy. This was also found for the first quarter, but not for the remainder of the total trial. It is possible that the less familiar strategy required more initial attention to fixate in the correct place.

A final methodological point for future studies using eye movement data concerns standardization of methods of analysis. Indeed, despite a large number of studies that have employed eye movements in different cognitive domains, there is still a lack of standardization in methods of analysis in the problem solving literature (this may be less of a concern in other cognitive domains such as reading; see Rayner, 1998). The choice of 60 ms for fixations was necessarily somewhat arbitrary, but was chosen in correspondence with minimum meaningful fixations others have studied including 50 ms (Hodgson et al., 2000), 60 ms (Liversedge & Findlay, 2000), and 100 ms (Verschaffel et al., 1994). Note that we were not measuring fixations per se but three or more consecutive points in the same zone – thus these were potentially different coordinates, with the constraint that they occurred within the same zone. “Fixations” were then summed into durations of total times when eye position rested on particular parts of the display, a procedure frequently reported in the eye movement literature (for example, Grant & Spivey, 2003; Hodgson et al., 2000).

Conclusions

In conclusion, this study showed a number of important findings that theories of complex arithmetic should take into account. Participants do not use a single strategy to solve complex addition problems; strategies differ in effectiveness; and young and older participants differed in strategy execution and selection. The study also showed that processing carries resulted in varying levels of performance and different eye movement patterns. Eye movement data provided validation of strategies and also showed less differentiation between strategies in older than young adults. This demonstrates the usefulness of eye movement data for investigating spatio-temporal distribution of attention during problem solving while using different strategies and age-related differences in these strategies and distributions.

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Appendix: Addition Problems

Block A	Block B	Block C
382 + 204	521 + 456	548 + 321
523 + 254	213 + 702	273 + 406
152 + 621	108 + 851	706 + 182
142 + 231	314 + 602	201 + 317
615 + 354	371 + 208	438 + 301
214 + 523	321 + 258	104 + 671
103 + 746	512 + 327	243 + 654
651 + 218	632 + 153	143 + 302
167 + 509	312 + 168	641 + 219
158 + 807	106 + 214	519 + 238
341 + 619	147 + 319	106 + 874
416 + 249	519 + 461	532 + 408
298 + 481	137 + 491	483 + 324
382 + 451	351 + 273	394 + 462
251 + 583	198 + 451	683 + 152
671 + 258	387 + 251	567 + 381
193 + 278	196 + 714	596 + 259
653 + 268	567 + 386	384 + 486
287 + 593	198 + 653	174 + 598
152 + 569	489 + 341	357 + 598
596 + 274	189 + 351	478 + 146
169 + 286	768 + 137	129 + 396
579 + 127	687 + 248	584 + 129
594 + 169	638 + 274	176 + 249

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Table 1Means and Standard Deviations of Participant Skills Tests and Self-Reports

Measure	Potential range	Young (<u>n</u> = 24)	Older (<u>n</u> = 24)	<u>F</u> (age)
Vocabulary	(0-32)	25.5 (3.9)	27.7 (2.2)	5.87*
Arithmetic	(0-240)	^a 63.1 (20.4)	94.8 (35.8)	14.25***
Mini Mental Status	(0-30)	29.8 (0.4)	29.0 (1.0)	16.07***
Health	(1-7)	5.6 (1.0)	5.4 (0.9)	0.43

^a Due to an error in administration, the young participants did not complete practice trials for the arithmetic test and completed only half the test. Their scores were doubled to estimate their scores on the whole test, but this remains an underestimate of their true scores.

* $p < .05$ *** $p < .001$

Table 2Means and Standard Deviations for Response Times (RT), Percent Error, and Strategy

Carries	NC Unit		NC Hundred		Choice		
	RT	% error	RT	% error	RT	% error	% unit strategy
<u>Young Adults</u>							
0	6.5 (1.7)	7.3 (9.7)	5.6 (2.4)	3.1 (5.5)	6.6 (2.7)	3.1 (5.5)	34.9 (31.3)
1	9.2 (3.3)	15.1 (12.8)	9.1 (5.1)	14.6 (10.9)	10.0 (3.8)	13.5 (14.2)	65.1 (27.1)
2	11.0 (3.5)	19.8 (19.1)	11.4 (5.6)	18.2 (15.2)	12.4 (5.1)	19.3 (16.1)	78.6 (26.4)
<u>Older^a Adults</u>							
0	8.1 (2.4)	9.9 (13.3)	7.2 (2.1)	4.7 (8.1)	7.9 (2.8)	9.9 (11.0)	45.8 (39.3)
1	10.5 (3.6)	19.8 (17.6)	10.4 (4.0)	20.8 (16.8)	11.2 (4.4)	17.2 (17.2)	57.3 (41.2)
2	12.5 (4.4)	30.7 (28.1)	13.2 (5.4)	24.5 (18.2)	12.4 (5.1)	31.3 (23.0)	64.1 (43.7)

^a Response times for no choice trials based on 23 older adults only, as one participant had zero correct trials in the no choice units condition.

Table 4F Values and Degrees of Freedom (Df) for Eye Position in First Second of the Trial

Effect	No Choice			Choice		
	Df	Duration	Fixation	Df ^a	Duration	Fixation
Age	1, 45	4.42*	4.11*	1, 34	0.24	0.00
Strategy	1, 45	15.62***	6.32*	1, 34	1.77	2.32
Digit	2, 90	24.27***	31.22***	2, 68	14.14***	14.13***
Carry	2, 90	0.37	1.39	-	-	-
Age x Strategy	1, 45	0.87	1.18	1, 34	0.28	0.00
Age x Digit	2, 90	1.33	1.45	2, 68	2.25	2.70
Strategy x Digit	2, 90	56.66***	54.75***	2, 68	5.07**	3.04
Age x Carry	2, 90	0.30	3.85*	-	-	-
Strategy x Carry	2, 90	0.16	3.44*	-	-	-
Digit x Carry	4, 180	2.57*	1.06	-	-	-
Age x Strategy x Digit	2, 90	12.26***	14.38***	2, 68	3.07	4.07*
Age x Strategy x Carry	2, 90	0.69	1.91	-	-	-
Age x Digit x Carry	4, 180	0.85	0.60	-	-	-
Strategy x Digit x Carry	4, 180	1.99	1.54	-	-	-
Age x Strategy x Digit x Carry	4, 180	1.35	1.04	-	-	-

* $p < .05$ ** $p < .01$ *** $p < .001$

^a Analyses of choice trials based on 22 younger and 14 older adults, as not all participants used both strategies in choice trials.

Table 5F Values and Degrees of Freedom (Df) for Eye Position Across the Length of the Trial

Effect	No Choice			Choice		
	Df	Duration	Fixation	Df ^a	Duration	Fixation
Age	1, 45	0.82	1.40	1, 34	2.11	1.90
Time	3, 135	23.04***	2.30	3, 102	8.72***	1.13
Strategy	1, 45	0.03	0.02	1, 34	4.24*	2.48
Digit	2, 90	33.39***	35.63***	2, 68	8.15***	10.86***
Carry	2, 90	66.72***	71.80***	-	-	-
Age x Time	3, 135	2.69*	0.11	3, 102	1.39	1.56
Age x Strategy	1, 45	0.05	0.47	1, 34	2.51	3.36
Time x Strategy	3, 135	9.65***	4.02**	3, 102	2.56	0.11
Age x Digit	2, 90	0.03	0.06	2, 68	6.76**	7.56**
Time x Digit	6, 270	11.35***	7.66***	6, 204	2.44*	1.41
Strategy x Digit	2, 90	0.09	0.11	2, 68	2.87	2.93
Age x Carry	2, 90	0.02	0.04	-	-	-
Time x Carry	6, 270	3.13**	1.08	-	-	-
Strategy x Carry	2, 90	3.27*	2.03	-	-	-
Digit x Carry	4, 180	18.97***	18.92***	-	-	-
Age x Time x Strategy	3, 135	1.70	2.10	3, 102	2.54	3.27*
Age x Time x Digit	6, 270	4.56***	2.88**	6, 204	1.28	1.80
Age x Strategy x Digit	2, 90	0.13	0.07	2, 68	0.04	0.02
Time x Strategy x Digit	6, 270	31.40***	36.12***	6, 204	4.73***	4.91***
Age x Time x Carry	6, 270	0.81	1.03	-	-	-
Age x Strategy x Carry	2, 90	0.08	0.01	-	-	-
Time x Strategy x Carry	6, 270	3.13**	1.55	-	-	-
Age x Digit x Carry	4, 180	0.86	0.75	-	-	-

Time x Digit x Carry	12, 540	4.12***	1.82*	-	-	-
Strategy x Digit x Carry	4, 180	1.73	0.71	-		
Age x Time x Strategy x Digit	6, 270	5.76***	8.66***	6, 204	2.20*	2.29*
Age x Time x Strategy x Carry	6, 270	1.21	1.94	-	-	-
Age x Time x Digit x Carry	12, 540	1.24	0.90	-	-	-
Age x Strategy x Digit x Carry	4, 180	0.33	0.28	-	-	-
Time x Strategy x Digit x Carry	12, 540	6.53***	5.11***	-	-	-
Age x Time x Strategy x Digit x Carry	12, 540	1.13	2.18*	-	-	-

* p < .05 ** p < .01 *** p < .001

^a Analyses of choice trials based on 22 younger and 14 older adults, as not all participants used both strategies in choice trials.

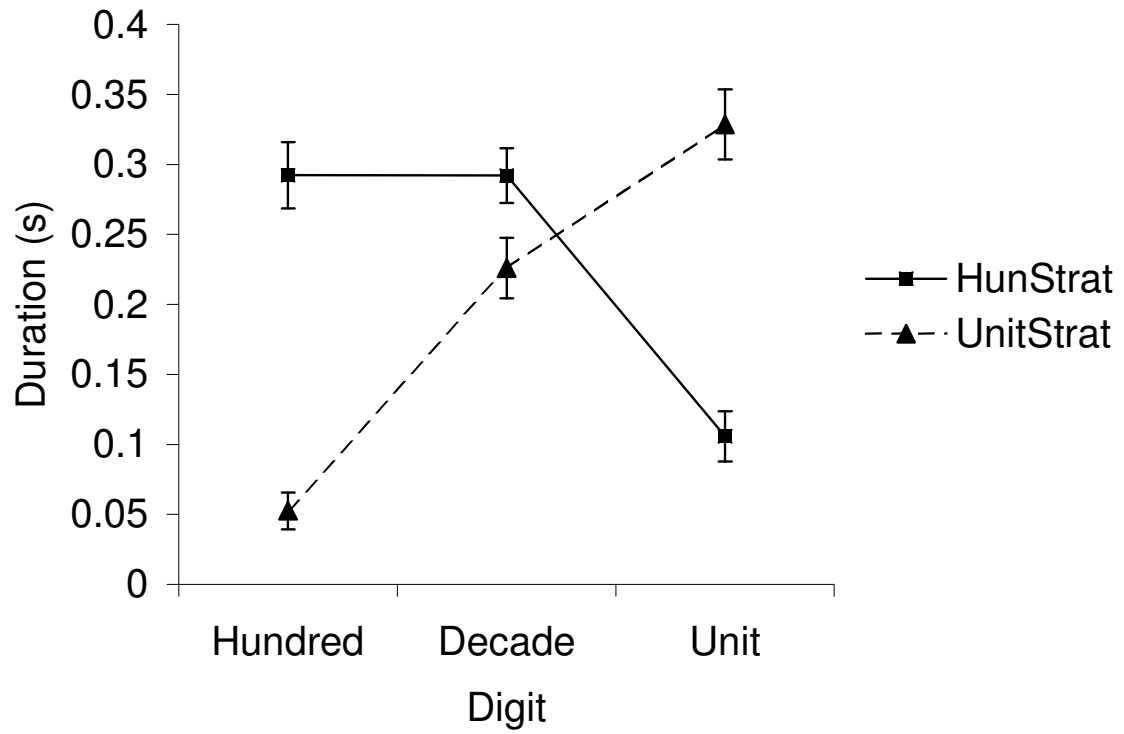
Figure Captions

Figure 1. Strategy x Digit interaction for cumulative duration in the first second of no choice trials, for (a) young adults and (b) older adults. HunStrat = Hundred strategy; UnitStrat = Unit strategy.

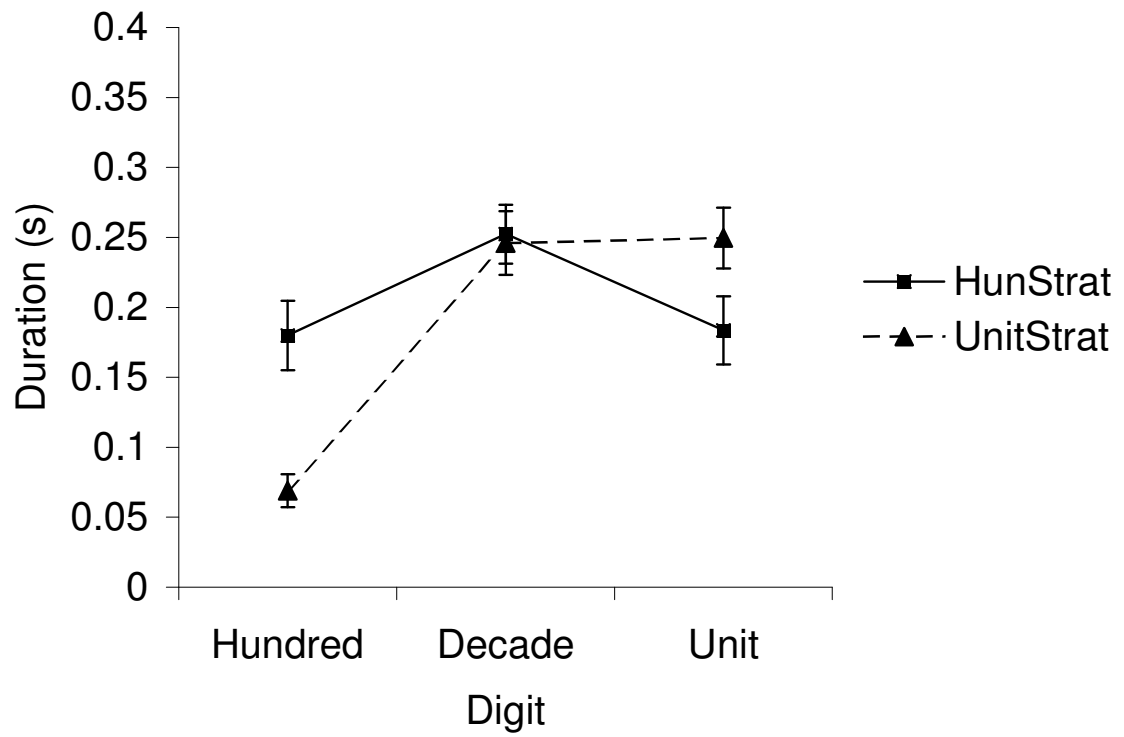
Figure 2. Strategy x Digit interaction for cumulative duration in the first second of choice trials, for (a) young adults and (b) older adults. HunStrat = Hundred strategy; UnitStrat = Unit strategy.

Figure 3. Cumulative duration over the four quarters of no-choice trials when using hundred and unit strategy, at (a) hundred (b) decade and (c) unit positions. Data for younger adults (Y) are shown with solid symbols and older adults (O) with open symbols. HunStrat = Hundred strategy; UnitStrat = Unit strategy.

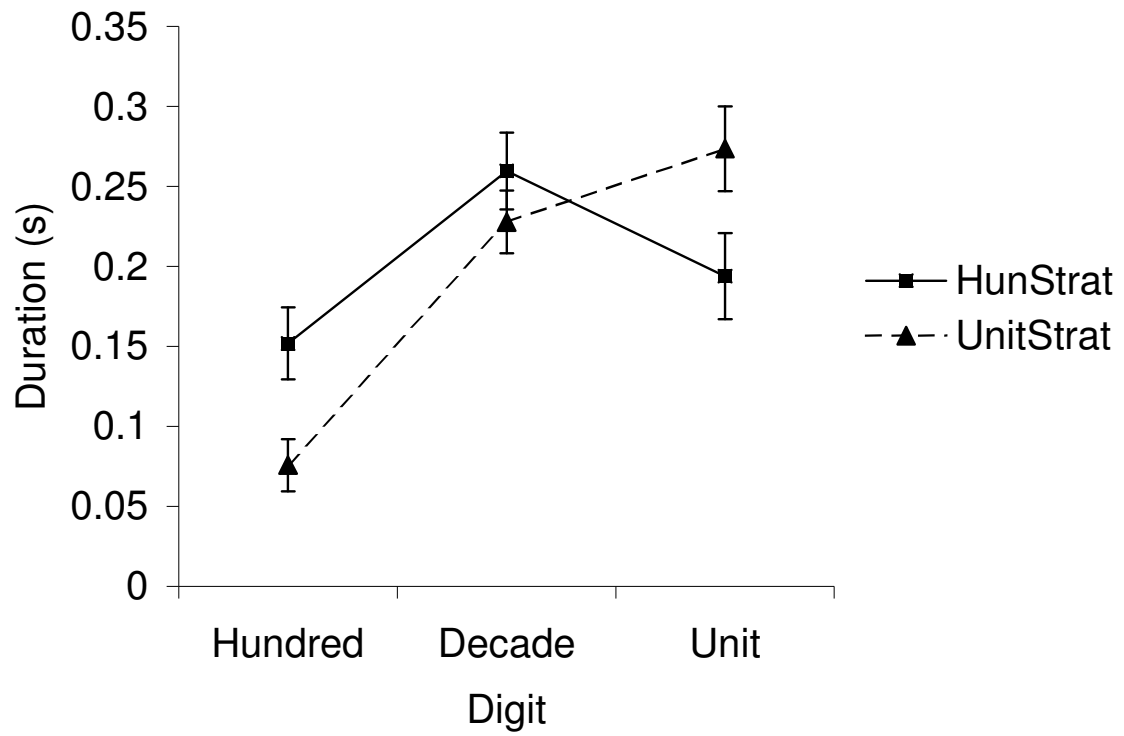
(a)



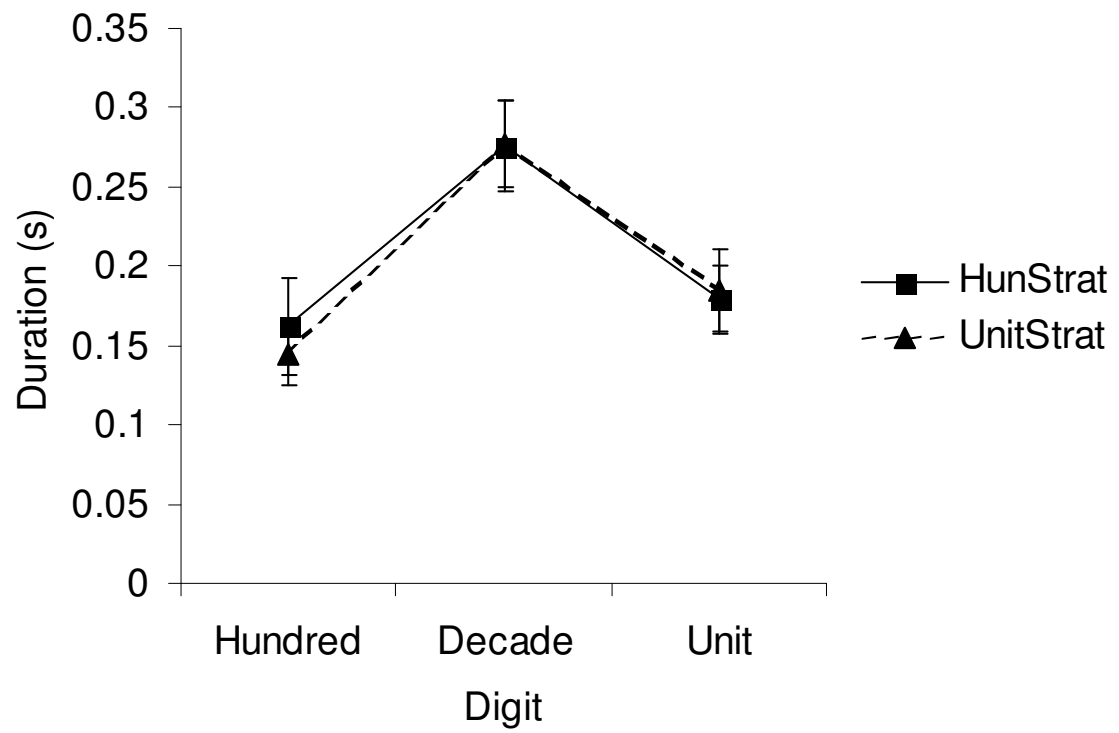
(b)



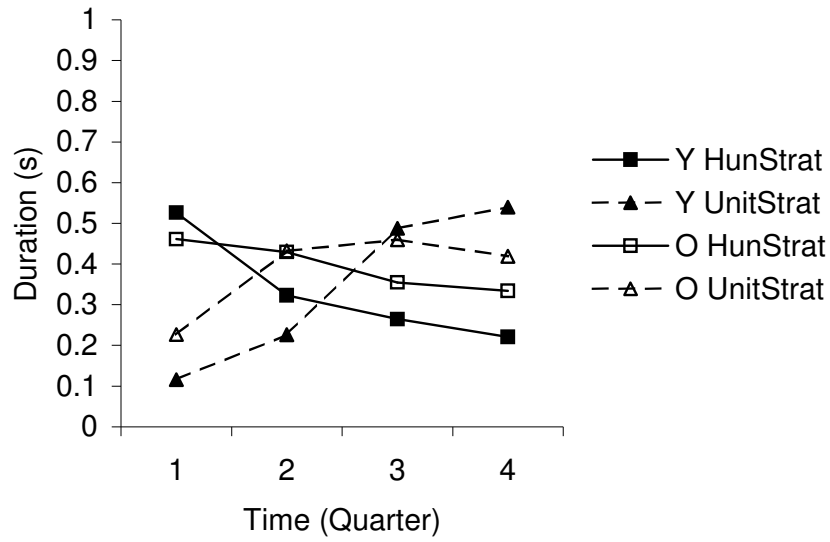
(a)



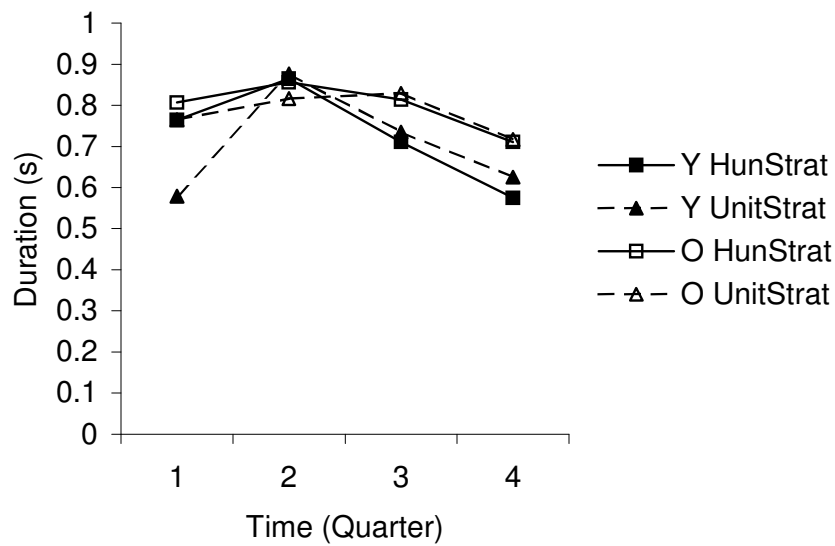
(b)



(a)



(b)



(c)

